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Emission Performance of California and Federal Aftermarket TWC Converters

Rasto Brezny and Joseph Kubsh
Manufacturers of Emission Controls Association

ABSTRACT

Original equipment (OE) catalytic converters are designed to last the life of properly tuned and maintained vehicles. Many high mileage vehicles require a replacement converter because the original catalyst was damaged, destroyed, or removed, and the cost of a new OE converter on an older vehicle is difficult to justify. In the U.S., a federal aftermarket converter program has been in place since 1986 (California in 1988) and it has resulted in the replacement of over 50 million converters. Both Federal and California programs have required aftermarket converters to meet minimum performance and durability standards.

Increasingly tighter emission standards and durability requirements for new light-duty vehicles have resulted in significant technology improvements in three-way automotive catalysts, however these advancements have not always made their way into aftermarket converters. California amended their aftermarket converter program in 2009, doubling the durability requirements and tightening the emission standards to match the original certification limits of the vehicles.

To evaluate the difference in emissions performance between the state-of-the art California Air Resources Board (ARB) aftermarket converters and those offered in the federal market, a test program was designed to compare the two technologies across five LEV I certified vehicles. Federal and ARB converters were aged over a RAT-A cycle to represent 25,000 and 50,000 equivalent road miles of aging. Fresh and aged converters were tested over the FTP-75 test cycle. The ARB converters reduced criteria pollutants by an average of 77% NOx, 60% HC and 63% CO below today's Federal aftermarket converters. The data indicates that significant emission benefits could be achieved by revising federal aftermarket regulations to match those required by California.

BACKGROUND & INTRODUCTION

The catalytic converter is an essential component of a light-duty vehicle's emission control system. In the U.S., new catalytic converters have been installed on passenger cars and light-duty trucks since 1975 to meet Federal or California light-duty vehicle emission standards. OE catalytic converters are designed to last the life of properly tuned and maintained vehicles. For model year 1998 and newer vehicles, this represents 120,000 miles (for some California-certified Partial Zero Emission Vehicle (PZEV) vehicles, the useful life is 150,000 miles).

Due to the high durability requirements necessary to last the full useful life (FUL) of a vehicle, the OE catalysts must use high levels of precious metals and other expensive materials. Over time, however, the emission reduction effectiveness of an OE catalytic converter may be severely degraded or even completely destroyed. Excessive vibration or shock, excessive heat, lack of proper vehicle maintenance, or improper vehicle operation can cause catalyst failures. Contaminants from lubricating oil such as phosphorus, calcium and zinc have been found to poison catalysts over time [1]. In addition, converters can be structurally damaged in accidents or if the vehicle hits an obstruction such as a large rock or debris on the road. If the vehicle is beyond its emissions warranty, the cost of a new original equipment converter can be prohibitive. Many vehicles requiring a replacement converter have considerably less than 100,000 miles of remaining life, making the cost of a new OE converter difficult to justify. Because of this, and the sometimes scarce availability of the original equipment converters for older vehicles, less expensive aftermarket converters give vehicle owners more incentive to replace their ineffective or damaged converters after the original emission warranty has expired.

About 10 years after catalytic converters were first introduced in the United States, Environmental Protection Agency (EPA) officials determined that a replacement catalytic converter program offering cost effective replacement for damaged converters on vehicles beyond their full useful life was needed. EPA estimated that the cost of purchasing a new OEM converter could range from $300 to $1,000. An aftermarket converter market began to develop, but some of these converters were inferior products, offering little or no pollution control capability. Without regulatory requirements, there was no way to determine whether these converters were performing properly or if they were installed on the right vehicles. In response, EPA established an aftermarket converter enforcement policy [2]. In the U.S., a Federal aftermarket converter program has been in place since 1986 (California began their program in 1988) and it has resulted in the replacement of over 50 million converters that were damaged, destroyed, or removed. Both the Federal and California programs have required that aftermarket converters meet certain minimum performance standards while also requiring installers to install only converters approved for specific vehicles.

The U.S. EPA aftermarket converter program requires that a catalytic converter demonstrate specific conversion efficiencies after 25,000 miles of operation. The metal shell and exhaust pipes must last 5 years or 50,000 miles. The emission reductions at the end of the 25,000 mile durability period must be at least 70% for HCs, 70% for CO, and 30% for NOx below engine-out levels. The EPA program requires that the manufacturer demonstrate, by testing over the EPA Federal Test Procedure (FTP-75) with a chassis dynamometer, that the emission performance requirements can be on a fully aged converter. To demonstrate this level of durability, two catalyst equipped vehicles must be driven over a prescribed route consistent with the driving schedule described in U.S. EPA regulation Title 40 CFR 86 Appendix IV [3] until the accumulated mileage has been achieved. A manufacturer may propose an alternatively accelerated bench aging of the converter that simulates 25,000 miles of service provided a correlation to vehicle road aging was previously demonstrated to EPA. Following the aging protocol, the manufacturer must demonstrate that the converter meets the above tailpipe emission conversion efficiencies.

In 1988, the ARB adopted its own regulations that permit the sale and installation of non-OEM replacement catalytic converters on California vehicles [4]. FTP conversion efficiencies of 70% for HC and CO and 60% for NOx after completion of a 25,000 mile converter durability demonstration was chosen primarily to provide some consistency with the EPA program while offering emission reductions beyond the Federal converter replacement policies. In 2001, California amended their aftermarket program to require aftermarket converters installed on vehicles equipped with On-Board Diagnostic (OBD) monitoring to carry a 50,000 mile warranty and be compatible with the OBD system by not illuminating the Malfunction Indicator Lamp (MIL) light over the full warranty period. Furthermore California allowed the use of the dynamometer RAT-A accelerated aging cycle [5] to demonstrate converter full useful life durability. Both programs allowed the sale of used or remanufactured converters which have been removed from salvage vehicles. These converters must pass a simple emissions test to insure a minimum level of performance, however, because the operating history is unknown, the remaining operating life cannot be guaranteed. The most cost-effective replacement converters are newly manufactured aftermarket converters. The catalyzed ceramic honeycombs in these aftermarket converters are manufactured by many of the same companies supplying OEM converters. Due to the lower durability requirements, manufacturers are able to use lower quantities of precious metals and other materials thus offering substantial cost savings to the consumer.

Although the function of a three-way catalytic converter (TWC) has remained relatively constant during its nearly forty years of use on light-duty gasoline vehicles, the primary converter components (catalytic coatings, substrates, mounting materials, stainless steels) have gone through a continuous evolution and redesign processes aimed at improving the overall performance of the converter [6]. These catalytic converter advances include improvements in catalytic converter washcoats, precious metal loading, and substrate designs, in combination with better vehicle fuel control systems [7,8,9]. A similar re-engineering effort has occurred with other exhaust system components, such as exhaust manifolds, oxygen sensors and exhaust pipes, that complement improvements in catalytic converter technology. A large driver in the continuous improvement processes for both catalytic converters and exhaust system components has been the adoption of increasingly tighter emission standards and durability requirements for new light-duty vehicles required by the Federal Tier 2 and California's LEV II regulations. The performance-based catalytic converter re-engineering effort has had three main focuses: wide application of close-coupled converters mounted near the exhaust manifold of engines, the development and use of high cell density, thin wall substrates, and the design of advanced, high performance TWCs for both close-coupled and under-floor converter applications.

Manufacturers have gained a greater understanding of the interactions between precious metal catalysts and the oxide support materials used in the washcoat [10,11,12]. The use of more thermally stable support materials and mixed oxides exhibiting important functionalities like oxygen storage have led to a new level of performance from these catalysts [13]. Significant advances have occurred in the coating of the substrate by positioning the precious metals on specific support materials within the washcoat layers to either promote specific reactions or protect the precious metal from poisons in the exhaust. Zone coating is another advance in catalyst coating technology which strategically locates precious metal functionality along the length of a channel, leading to further innovations in converter architecture [14]. These advances combine to produce catalysts that can survive high temperature exposure and deliver higher levels of performance over a longer useful life. Due to stricter regulatory requirements, new vehicles and aftermarket converters sold in California have most benefited from these technological advances.

Another significant advancement that occurred in the 1990s was the implementation of on-board diagnostic (OBD and in 1989, OBD II) systems on new light- and medium-duty vehicles (starting with the 1996 model year). These systems use sensors, such as oxygen sensors in the exhaust, and a vehicle's on-board computer to monitor the performance of its emission control systems, including the catalytic converter. This has given regulators a way to ensure that the emission control system and catalyst are functioning properly over the full useful life of a vehicle. To ensure that aftermarket catalysts are compatible with the OBD II system and do not cause the vehicle's MIL to illuminate when the catalyst is functioning properly, manufacturers have implemented tight quality control procedures in their processes.

Beginning in California, in 2009, these new materials and coating technologies have been applied to advanced OBD II-compliant aftermarket converters, as well as more durable aftermarket converters for older, pre-OBD vehicles, to achieve significant reductions of HC and NOx emissions from California's existing passenger fleet [15]. This meant that the aftermarket converters had to be fully OBD II-compliant and function just like the OEM converter but with somewhat lower durability requirements of 50,000 miles. The OBD emission thresholds for aftermarket converters are slightly higher to allow for a single technology to cover a broader set of vehicles. In California, the aftermarket converter must meet the same emission limits to which the vehicle was originally certified.

The benefit of installing the latest aftermarket catalyst technology on non-OBD vehicles was demonstrated in testing conducted by ARB in 2006 and discussed in their Staff Report supporting their October 2007 proposed rule [4]. Fourteen pre-OBD test vehicles were selected that averaged 140,000 to 160,000 odometer miles and that passed the state Smog Check inspection to eliminate any that may have had engine related emission problems. Five of the vehicles were fitted with aftermarket catalysts that met the pre-2009 standards for non-OBD II vehicles. The remaining nine pre-OBD vehicles were fitted with aftermarket converters manufactured using the latest catalyst technology. After approximately 8,000 miles of real world operation, the advanced aftermarket catalysts resulted in 50-75% lower emissions of all three criteria pollutants compared to the older aftermarket catalyst technology. Furthermore, the advanced catalysts demonstrated far better durability, resulting in 60% less deterioration in HC emissions and 75% less deterioration in NOx emissions after only about 8,000 miles of real world mileage accumulation relative to older aftermarket converters.

The data generated by the California Air Resources Board compared pre-2007 aftermarket converters sold for pre-OBD vehicles (pre-1996) against the state-of-the-art technology that was being sold for OBD-equipped vehicles. The pre-OBD technology complied with the 70% HC, 70% CO and 60% NOx reduction requirements and carried a 25,000 mile warranty whereas the OBD-compliant aftermarket converters had to last 50,000 miles while still meeting the certified emission limits of the vehicle. Outside of California, the aftermarket converters are only required to meet the U.S. EPA aftermarket converter requirements of 70% HC, 70% CO and 30% NOx reduction and carry a 25,000 mile warranty.

There are large parts of the country, such as parts of Texas and the Northeast that remain out of attainment for ozone. Tighter new vehicle standards are one way to clean up the passenger vehicle fleet. However, it takes over 10 years to turn over that fleet. Based on annual member surveys conducted by MECA, there are approximately three million aftermarket converters sold every year across the country. One mechanism to accelerate the upgrading of the passenger fleet to the most advanced TWC catalyst technology would be to implementing tighter aftermarket converter requirements in parallel with tighter new vehicle standards.

Since MECA members manufacture and sell both types of technology, we wanted to measure the emission benefits of the most advanced California aftermarket converter technology as a way of quantifying what the emission benefits might be available across all 50 states if EPA were to revise their aftermarket converter program to match ARB's requirements. MECA members initiated this test program to generate the necessary data to allow Federal and state regulators to better model the emissions impacts of a revised Federal aftermarket converter policy and make the most cost effective decisions to improve the emissions performance of the existing light-duty passenger car and truck fleet.

EXPERIMENTAL PROCEDURE

Emissions measurements were carried out on five different LEV I certified OBD-equipped vehicles to represent the range of engine displacements and exhaust configurations across the light-duty fleet. Vehicles included both passenger cars and light-duty trucks having either single or dual exhaust systems. Engine displacements included four, six and eight cylinders and model years ranging from 1999 to 2002. Four of these vehicles represent the worst case emitting vehicles used by ARB to certify pre-OBD II aftermarket catalysts [16]. Table 1 gives the specifications for the five vehicles tested in this program.

Aftermarket converters used in this study comprised commercial converters manufactured to meet either Federal, or California requirements, and being marketed for the respective test vehicles. Converters and test vehicles were supplied by MECA members and testing was conducted at certified laboratories used to perform vehicle emissions testing for agency approval. The vehicles in their OEM configuration were tested to insure that they would pass the California Smog Check.

Table 1: Five Test Vehicles used to Evaluate Aftermarket Converters

Make - Model	Year	Cylinders	Engine Displacement (liters)	Exhaust Configuration
Volkswagen - Jetta	1999	4	2.0	Single
Chevrolet - Camaro	2000	6	3.8	Single
Mercury-Grand Marquis	1999	8	4.6	Dual
Ford - F-150	2002	8	5.4	Dual
Dodge - Durango	1999	8	5.9	Single

Fresh converters were preconditioned using a 50 mile on-road cycle as required under the ARB aftermarket testing protocol [7]. Emissions tests were performed over the light-duty FTP-75 test cycle and results represent weighted emission values for the three stages of the test cycle. Values represent single measurements for fresh converters and the average of two FTP tests on aged converters. A matching set of converters for each vehicle were aged using the Accelerated Rapid Aging Test cycle (RAT-A) on an engine aging dynamometer as required by the ARB regulation [7] to represent 50,000 mile equivalent on-road aging. Maximum catalyst aging temperatures observed during the aging cycle were approximately 925 °C as measured one inch up stream of the catalyst face. As stipulated by the ARB regulation, converters for passenger cars were aged for 75 hours and converters for trucks were aged 100 hours using the RAT-A schedule.

Based on MECA member experience with exhaust temperatures during the driving cycle described in Title 40 CFR 86 subpart IV, a 25 hour RAT-A dynamometer aging was selected to represent a worst case example of the 25,000 miles of road aging as required under the Federal aftermarket program. A separate set of Federal converters were aged to the ARB full useful life limit with 75 and 100 hours of RAT-A aging for cars and trucks, respectively.

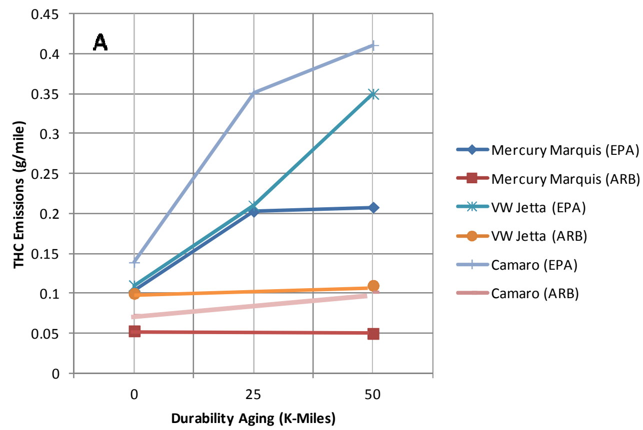
The aged converters were installed on the vehicles and tested for their weighted emissions of total hydrocarbons (THC) non-methane hydrocarbons (NMHC), carbon monoxide (CO) and oxides of nitrogen (NOx) over the FTP-75 test cycle. Replicate tests were run using the fully aged converters to make sure that results were within 10% of each other.

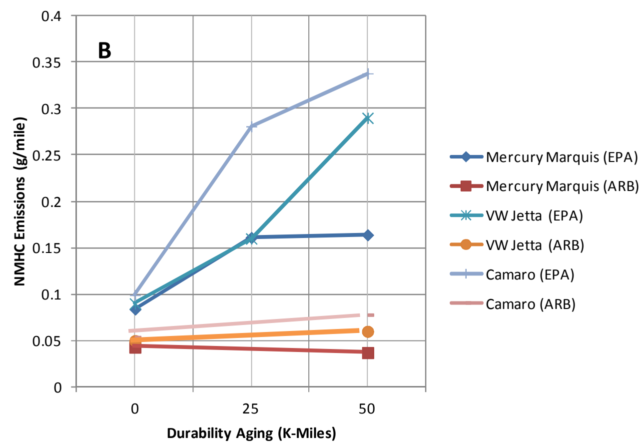
RESULTS AND DISCUSSION

The weighted FTP results for each criteria pollutant were calculated for the passenger cars and trucks. Figure 1 shows the emission levels for the three passenger vehicles tested. The passenger car data show a significant difference between the deterioration rates of the Federal converters and the California certified converter technology for all three vehicles. There are several important points to keep in mind. The U.S. EPA approved technology only has to show a level of reduction in the 25,000 mile aged condition of 70% for total hydrocarbons, 70% for CO and a 30% reduction of NOx. In this study we also aged the Federal converters out to 50,000 equivalent miles to provide a level of comparison with a fully aged ARB converter. The data also gives some indication of the deterioration rate of the Federal converters if they remain in use beyond their warrantee period. The ARB converters were not tested at the 25,000 equivalent mile cut point, however, for the sake of comparison we interpolated the straight-line fit of the ARB converter emissions at the 25,000 mile aging point.

California requires that aftermarket converters meet the emissions limit that the vehicle was certified to after full useful life aging of 50,000 equivalent miles. Furthermore if the MIL of the OBD II system is activated, the emissions may not exceed the certification limit by more than 2.6 times. This is 1.5 times greater than the OEM OBD threshold requirement of 1.75 times the emission limit. This flexibility provides aftermarket manufacturers some opportunity for broader vehicle coverage and to reduce the cost of the aftermarket converter. In general, manufacturers of OBD compliant aftermarket converters must use higher levels of precious metals to ensure that the emissions are not exceeded at the point of MIL illumination triggered by the engine control unit (ECU).

In some instances, such as the THC and NOx emissions for the Volkswagen Jetta or the NOx emissions on the Mercury Marquis, the fresh ARB and Federal converters showed almost the same emission level. The much higher deterioration rate of the Federal converters resulted in a higher emission level after the 25,000 mile aging and even higher after aging for 50,000 equivalent miles. All of the Federal aftermarket converters met the U.S. EPA requirement for percent reduction relative to the engine-out emissions. The combined requirement of meeting the OEM certification emission limit and being fully compliant with the OBD system associated with the ARB converters resulted in significantly lower emission levels out to 50,000 miles. In fact the deterioration factor for some of the ARB certified converters, such as the eight cylinder Mercury Grand Marquis, or four-cylinder Volkswagen Jetta were near one over the full useful life.





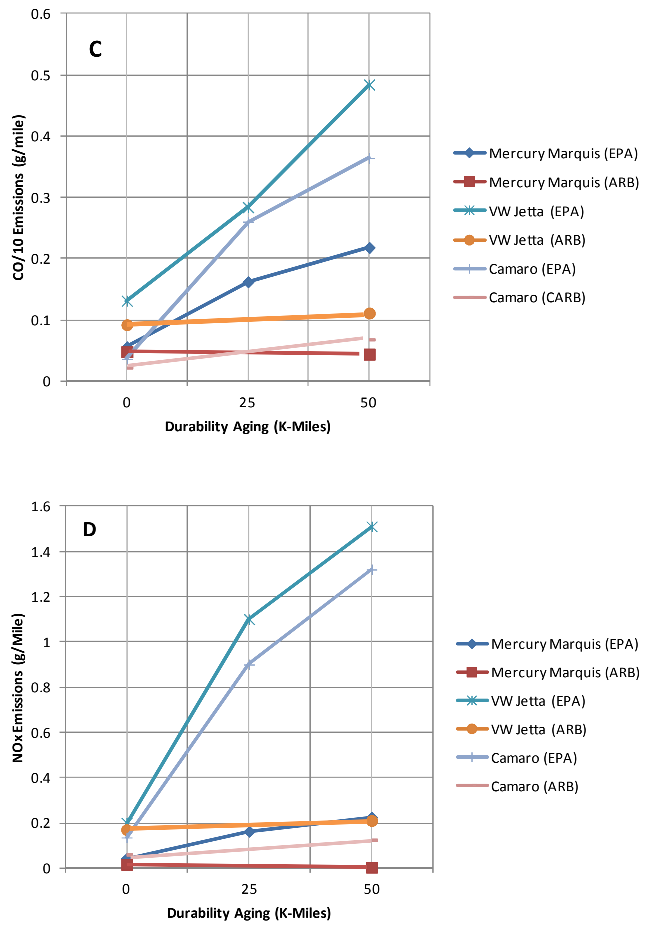


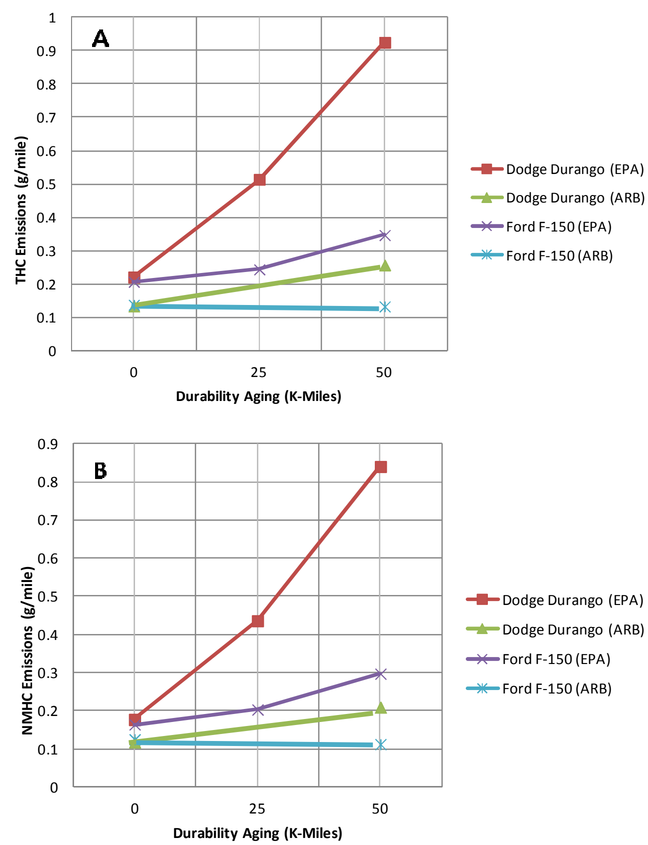
Figure 1: Criteria pollutant emissions in weighted g/mile for the three passenger vehicles equipped with aftermarket converters plotted versus aging in thousands of equivalent miles for: A) THC, B) NMHC, C) CO divided by 10 and D) NOx

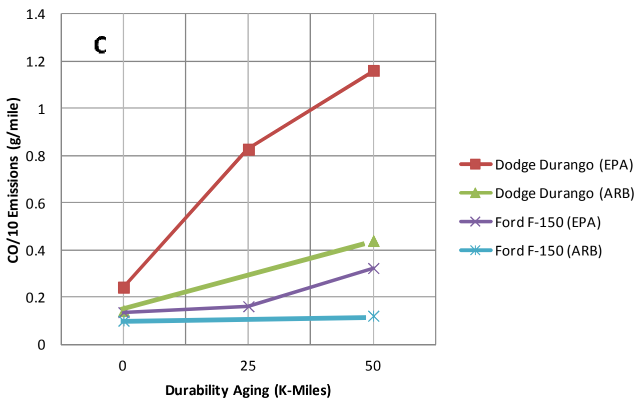
To estimate the emissions benefit between the two generations of catalyst technologies after 25,000 miles, one can interpolate the ARB emission levels at the 25,000 mile aging point. This provides a side-by-side comparison of the two technology classes because the Federal aftermarket converters were never designed to function out to 50,000 miles of driving. All three ARB converters exhibit an emission benefit of at least 50% to 75% for THC and CO and a much higher advantage of 90 - 94% additional NOx reductions at the mid-level aging point over the Federal catalysts. These differences in emissions increase to 70-80% for HC and CO and 85 – 98% for NOx after 50,000 miles of aging. The deterioration of THC emissions for the Federal converter was most significant on the Jetta as the slope increases beyond the 25,000 mile point. The magnitude of the NOx emission level was the highest for the Jetta and Camaro equipped with Federal converters with approximately 1 g/mile of NOx being emitted after FUL aging. An average of the three passenger car converters reveals an emission reduction advantage of 67% THC, 73% CO and 89% NOx when using the ARB approved converters after the U.S. EPA FUL aging of 25,000 miles. The benefit increased to 76% HC, 79% CO and 92% NOx after the full ARB aging of 50,000 miles.

A comparable data set for the two light-duty truck models is plotted in Figure 2. The same general conclusions can be made as were discussed for the passenger cars above. The noticeable difference between the respective converters on the two vehicles is most likely associated with differences in the engine-out emissions of the vehicles and the exhaust configuration.

Both vehicles have eight-cylinder engines, however the Durango has a single underfloor catalyst in a single exhaust configuration whereas the F-150 uses dual exhaust systems each having close coupled and underfloor catalyst elements for a total of four converters.

Upon closer inspection, the data in Figure 2 reveal that after 25,000 miles of aging the two aftermarket converter technologies for the F-150 perform similarly for CO and NOx. The ARB converter technology on this vehicle still offers a 30-40% benefit over the Federal aftermarket converter for all four criteria pollutants after the first 25,000 miles of aging. The benefit increases to 60% for HC and CO and 80% for NOx after the full 50,000 mile aging. The Durango, equipped with an ARB converter, offers a 60% advantage for HC and CO and an 85% benefit in NOx reduction versus the Federal converter over the entire aging period. The emission level for the Durango equipped with an EPA aftermarket converter is approximately 3 g/mile of HC + NOx weighted on the FTP after the mid-aging point, increasing to almost 5 g/mile after 50,000 miles.





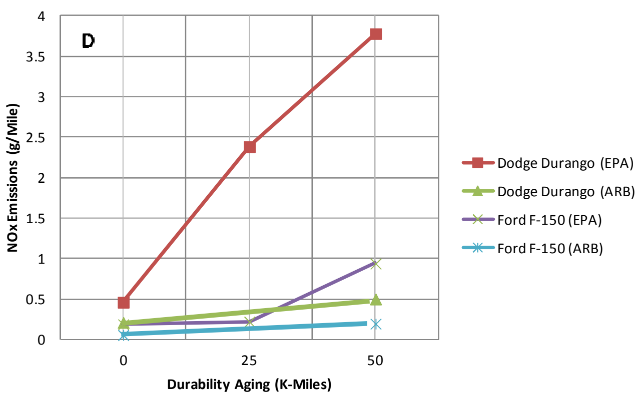


Figure 2: Criteria pollutant emissions in weighted g/mile for the two light-duty trucks equipped with aftermarket converters plotted versus aging in thousands of equivalent miles for: A) THC, B) NMHC, C) CO divided by 10 and D) NOx

The Clean Air Act, under Section 177, allows states to adopt either U.S. EPA or ARB new light-duty vehicle emission standards including aftermarket standards. Today there are 12 states that have adopted California LEV II standards, however the implementation of ARB's aftermarket standards varies from state to state. In most Section 177 states, the prior generation California's aftermarket converters are required on ARB certified vehicles however it is unclear how actively this is enforced. California allows only ARB approved aftermarket converters to be sold in the state and installed even on federally certified vehicles. Outside of California, only the states of New York and Maine have adopted California's aftermarket converter standards in December 2012. New York will begin enforcing the new aftermarket requirements on June 1, 2013.

The results of this study emphasize the emission benefits of advanced aftermarket converter technology applied to existing light-duty gasoline vehicles. As the fleet of new vehicles is becoming cleaner and the trend is for vehicle owners to hold onto their older cars longer, Section 177 states that are in non-attainment with the current National Ambient Air Quality Standard (NAAQS) for ozone might consider adopting California's aftermarket converter program as a way of achieving their State Implementation Plan (SIP) objectives. As EPA considers further tightening of the ozone NAAQS limit in the future, offering states a revised Federal aftermarket program similar to that implemented by California would provide an important ozone reduction tool to those states that have not adopted California's aftermarket converter standards.

CONCLUSIONS

New vehicle regulations have driven technology development for three-way catalysts resulting in lower emission levels on Tier 2 and LEV II certified vehicles. This has included advances in ceramic substrates, catalyst support materials, catalyst coating strategies and converter design to deliver over 99% reduction of criteria pollutants from the engine-out levels on the cleanest vehicles. Third-party aftermarket converters, sold outside of California, have not benefited from the same catalyst technology advancements. This becomes significant when looking at a states' total emissions from the light-duty fleet because some of the benefits achieved from new vehicles are lost by allowing inferior replacement converter technology to be installed on existing vehicles as they age. In 2009, California addressed this problem by requiring that new aftermarket converters meet the same emission limits as the original vehicle while allowing a shorter warranty life of five years or 50,000 miles to reduce the costs of aftermarket converters relative to OEM replacement parts. The Federal aftermarket program, on the other hand, allows new aftermarket converters to only reduce the engine-out emissions by 70% for hydrocarbons, 70% for CO and 30% for NOx. To quantify the emission benefit of ARB versus Federal aftermarket converters, MECA selected five test vehicles to represent the most common engines and exhaust configurations in the U.S. fleet. The vehicles tested included 4, 6 and 8-cylinder passenger cars, an SUV and light-duty pick-up truck. Commercial aftermarket converters designed to meet Federal and ARB emission requirements were aged out to 25,000 and 50,000 equivalent miles using dynamometer aging on the RAT-A cycle. The aged converters were installed on the vehicles and tested over the FTP-75 cycle. The average emission benefit for the five vehicles was found to be 77% lower NOx, 60% lower HC, and 63% lower CO emissions by using the latest ARB aftermarket converter technologies versus a Federal aftermarket converter.

The results suggest that reducing emissions from the in-use passenger fleet could be an important tool towards achieving national ambient ozone targets in nonattainment regions of the country. The significance of this opportunity is further emphasized as the U.S. EPA considers further tightening of the ozone NAAQS in the 2013 timeframe.

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CONTACT INFORMATION

Rasto Brezny
Manufacturers of Emission Controls Association
2020 North 14th Street
Suite 220
Arlington, VA 22201

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